DESIGN CONSIDERATIONS FOR RADIAL KEY RETROFIT

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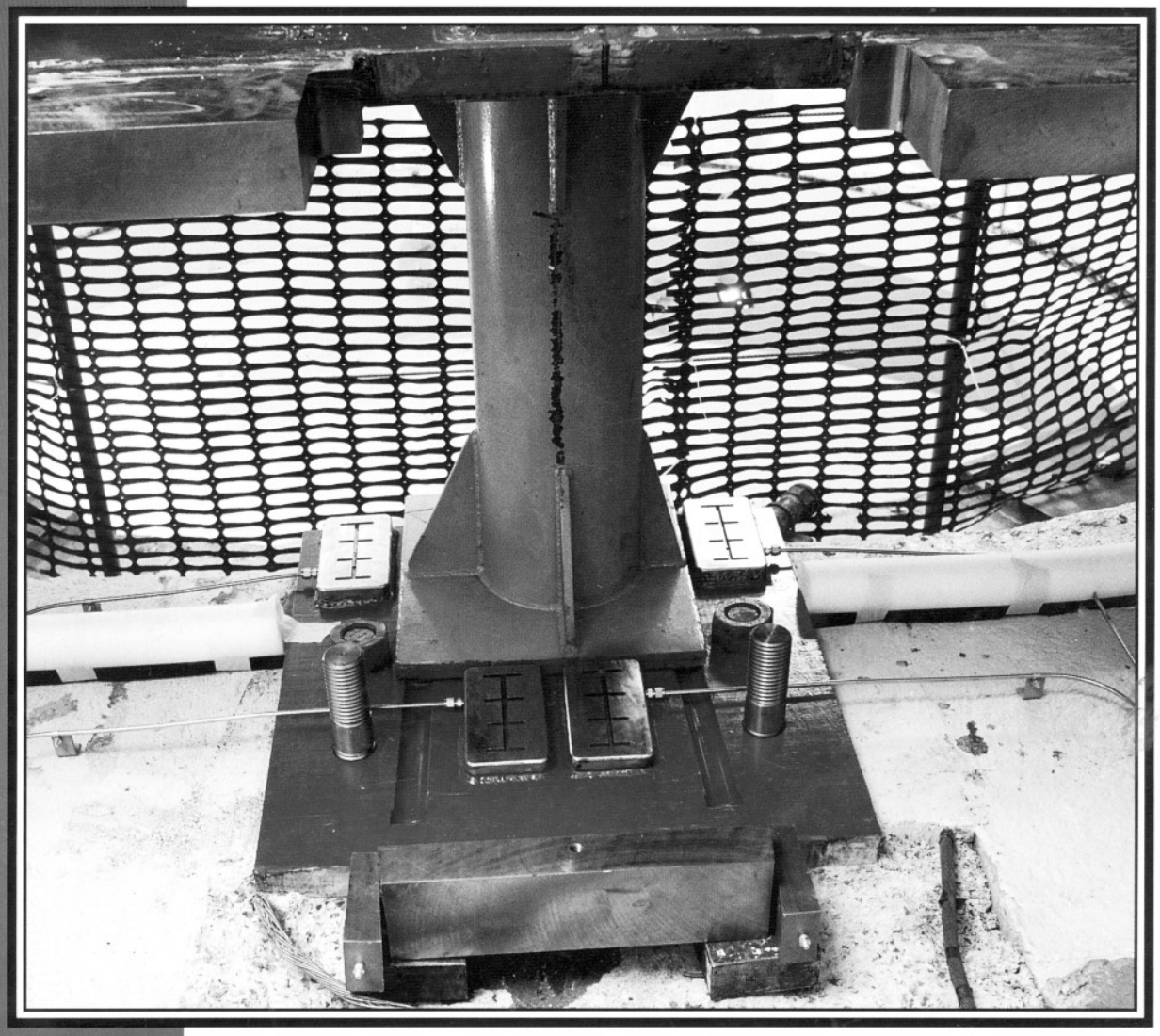

A practise that is becoming more and more common is to retrofit hydro-electric generators with Radial Key Systems. There are significant design considerations that must be made to ensure that a radial key retrofit leads to trouble free operation of the generator. This paper discusses considerations related to stress, vibration and stability in the design of a radial key retrofit. A typical design is outlined along with a method of increasing stator radial stiffness without restraining stator frame thermal expansion.

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Design Considerations For Radial Key Retrofit

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ABSTRACT

A practise that is becoming more and more common is to retrofit hydro-electric generators with Radial Key Systems. There are significant design considerations that must be made to ensure that a radial key retrofit leads to trouble free operation of the generator. This paper discusses considerations related to stress, vibration and stability in the design of a radial key retrofit. A typical design is outlined along with a method of increasing stator radial stiffness without restraining stator frame thermal expansion.

1.0 Introduction:

As existing power stations and their generators continue to age, design improvements continue to be found. The radial key retrofit is an example of such an improvement. Radial key systems permit free thermal expansion and contraction of the stator assembly. This results in reduction of stator core waves. Furthermore, if designed properly, they can provide a means of easily re-centering the stator. This feature is especially important in power stations that have concrete growth and component related distortion problems.

The retrofit design of a radial key system imposes a large number of design constraints on the design engineer since the machine and its environment already exist. The retrofit must be designed to ensure that the forces generated are supported in an effective manner. In addition, the implementation of radial keys dictates that the soleplate no longer provides radial restraint for the stator frame. The effects of this reduction in stiffness need to be considered.

The need for radial keys and considerations that should be given to their design and implementation will now be outlined.

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2.0 The Need for Radial Key Systems

A radial key retrofit can be implemented for one of the following reasons:

a) Core Waves are present
b) Stator frame failures
c) Power house concrete is shifting

2.1 Core Waves:

The Stator Core and Frame assembly of a Hydroelectric generator is a flexible structure which is typically anchored to the powerhouse foundation at the soleplates. The purpose of the stator core is to provide a magnetic flux path and to support the stator winding. The stator frame is used to restrain the core torsionally and maintain the desired air-gap.

During normal operation, open circuit core losses and I^2R stator winding losses are generated . These losses heat the stator core. The ventilation air that is used to cool the windings and core typically travels radially through the core and heats the stator frame before entering a heat exchanger. The result is that the stator frame also experiences a temperature increase. The core temperature is typically 10 to 20 deg C higher than the stator frame temperature. This temperature differential can be the prime cause of core waves.

The core and stator frame can be modelled as two concentric rings as shown in Fig 1. Since the stator frame is at a lower temperature than the core, it tends to restrain the core from expanding. The interference pressure between the stator frame and the core is readily shown to be (Kellenberger, W., 1966) :

$$p=\frac{\alpha\, r\, E(\Delta tc-\Delta ts)}{\frac{r_s^2}{A_s}+\frac{r_c^2}{A_c}} \qquad (1)$$

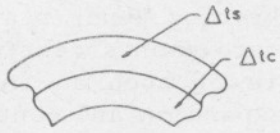

FIGURE 1 TWO CONCENTRIC RINGS

From equation (1), it is evident that the interference pressure is inversely proportional to the interface radius and directly proportional to the stator frame and core cross-sectional areas. The effect of this interference pressure is to induce the following tensile hoop stresses in the stator frame and compressive hoop stresses in the stator core:

$$\sigma_c=\frac{-p\, r}{A_c} \qquad \sigma_s=\frac{p\, r}{A_s} \qquad (2)$$

Substituting (1) into (2), we have the hoop stress expressions as given by (Kellenberger, W., 1966):.

$$\sigma_c = \alpha\,(\Delta t_c - \Delta t_s)\,E\,\frac{\left|\frac{r}{r_c}\right|^2}{1+\left|\frac{r_s}{r_c}\right|^2\frac{A_c}{A_s}} \quad (3) \qquad \sigma_s = \frac{A_c}{A_s}\sigma_c \quad (4)$$

In a free state, an increase in a ring's temperature will lead to an increase in its circumference. Therefore its radius will also increase. Since the core experiences a larger temperature rise than the stator, it becomes radially restrained by the stator. This restraint induces compressive hoop stresses in the core. If the stresses become sufficiently high, the core will buckle out of the plane of the ring in an attempt to relieve these stresses by increasing its circumferential length. (see Fig 2)

Determining the stress at which core buckling will occur is not trivial. Kellenberger, (Kellenberger, 1966) has given one solution as:

$$\sigma_k = \frac{E\,I}{4\,A_c\,r_c^2}\,\frac{(z^2-4)^2}{(z^2+\frac{8}{3})} \quad (5)$$

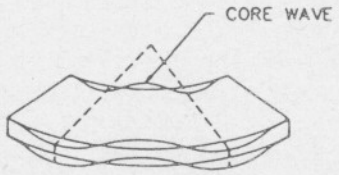

FIGURE 2 OUT OF PLANE BUCKLING

As one would expect, the above equation is similar in form to the well known Euler buckling formula. It has terms to account for ring torsional rigidity and wavelength. From equation (5), we see that the critical buckling stress varies inversely with the square of the core radius. This idea is borne out by industrial experience. Core buckling tends to be more prevalent in larger diameter generators.

Predicting the occurrence and degree of buckling is difficult for the following reasons. Calculating the effective rigidity of a stack of laminations is complex and the stresses given by equations (3)-(5) do not include the effects of soleplate, bracket and auxiliary restraints. Calculating the degree of buckling is difficult due to the variation in radial stiffness with axial position. The above analysis however, does show qualitatively how a reduction in stator radial restraint will reduce the severity of stator core waves.

One way of reducing the presence of core waves is to reduce the restraint imposed on the core by the stator frame. This reduction can be obtained by implementing radial keys between the stator frame and the foundation. The beneficial effects of radial keys in reducing core wave have been documented by O'Kelly (O'Kelly, 1981).

2.2 Stator Frame Failures

The interface pressure between the core and the stator frame is usually transmitted to the stator frame through the core studs/ bars.

These bolts are usually welded to the stator frame rings as shown in Fig 3. In peaking applications , these welds can fail under low cycle fatigue. Installing radial keys to reduce the transmitted loads can help to remedy this problem.

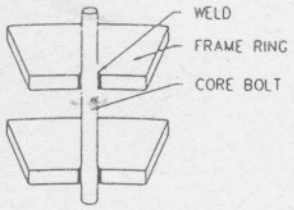

FIGURE 3 STATOR CORE BOLT FAILURES

2.3 Concrete Creep.

Thus far, only problems induced by thermal gradients have been considered. Another phenomenon that can cause significant distress to a hydrogenerator is concrete creep. The concrete foundations in which the stator soleplates are embedded can, under certain conditions, creep. Since the stator soleplates are firmly attached to the stator frame, the effect is that the concrete movement changes the stator shape and position. This action results in a change in the uniformity of the airgap around the generator stator circumference.

Non-uniform airgaps, generated by stator distortion can result in fatigue loading of the rotor as the rotating field pole moves from large to small air gaps. This non-uniformity has led to the failure of a rotor rim support ledge, resulting in substantial winding damage as the ledge broke loose from the spider arm and entered the end winding. This occurrence emphasizes the need to maintain an even airgap.

Radial key systems help minimize distortion due to concrete creep by permitting the concrete to move radially relative to the stator frame. The benefits of installing radial keys at the R.H. Saunders G.S. to overcome concrete creep have been documented by Lyles (Lyles, 1985). Before the installation of radial keys, the creep had been so severe that it led to rotor-stator rubbing. Upon installation of a radial key system, the creep induced distortion effects were significantly reduced.

3.0 Design Considerations

In the retrofit design of a radial key system, many factors must be considered to ensure that the benefits of radial freedom are obtained without inducing other problems.

3.1 Magnetic Stability:

The generator rotor, airgap and stator comprise an elastic system. We can model the system as shown in Fig 4

Some important aspects of this system are:

1) The field poles act as large electromagnets creating a magnetic attraction between the poles and the stator core.

2) The attractive force varies inversely with the airgap dimension. As the airgap gets smaller, the magnetic attraction increases according to:

$$Fmag = Kmag\ \delta \quad (with\ saturation) \quad (6)$$

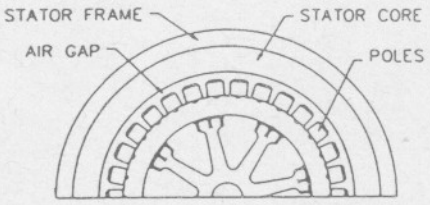

FIGURE 4 THE ELASTIC SYSTEM

In the design of the generator, one must ensure that the resistive forces generated due to a deflection of either the stator or rotor are greater than the corresponding increase in magnetic attraction due to the reduction in airgap. If this condition is not met, the system is unstable and rotor-stator contact can easily occur.

This phenomenon is analyzed by considering the stiffnesses of the various assemblies and can be modelled as shown in Fig 5

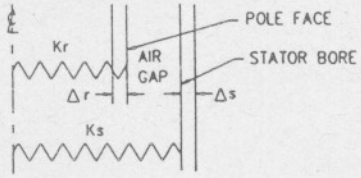

FIGURE 5 STIFFNESS MODEL

For a given attractive force, the rotor and stator move:

$$\Delta r = \frac{Fmag}{K_r} \quad (7) \qquad \Delta s = \frac{Fmag}{K_s} \quad (8)$$

The total reduction due to Fmag is:

$$\Delta t = \Delta r + \Delta s = Fmag \left| \frac{1}{K_r} + \frac{1}{K_s} \right| \quad (9)$$

$$Fmag = \left| \frac{1}{K_r} + \frac{1}{K_s} \right|^{-1} \Delta t \approx K_s\, \Delta t \quad (10)$$

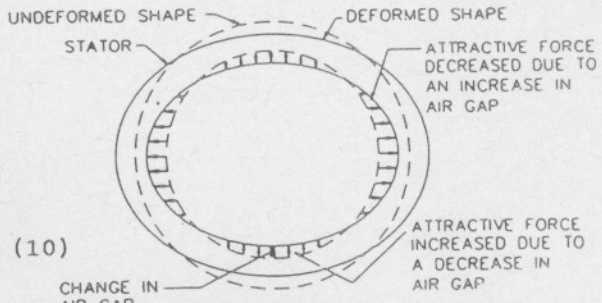
UNDEFORMED SHAPE
DEFORMED SHAPE
STATOR
ATTRACTIVE FORCE DECREASED DUE TO AN INCREASE IN AIR GAP
ATTRACTIVE FORCE INCREASED DUE TO A DECREASE IN AIR GAP
CHANGE IN AIR GAP

FIGURE 6 POLE FORCES

For this discussion on stators, we will assume a rigid rotor. Rotor stability has been treated by Martin (Martin, 1981).
For the system shown in Fig 6, the Magnetic and elastic stiffnesses are:

$$Kmag = \frac{B^2\ Rag\ l}{g} C_p\, C_u \quad (11) \qquad K_s = Kcbs\ \frac{E\ I}{R^3} \quad (12)$$

The determination of the stator stiffness is difficult for the following reasons:

1) The stator core is composed of many sector punchings clamped together. This assembly requires that friction transfer bending moments from punching to punching.

2) There is not complete coupling between the stator core and stator frame by the core studs/bars.

A measure of the system stability is given by the ratios of the magnetic and elastic stiffnesses.

$$C_{stab} = \frac{K_m}{K_s} = \frac{B^2 Rag\ R^3 l C_p C_u}{g\ E\ I\ Kobs} \quad (13)$$

If this stability factor C_{stab}, is less than 1.0, the system is stable.

It should be noted the stability factor is proportional to R to the fourth power (Rag * R^3). Therefore, we might expect stability problems with large diameter machines.

In the past, it was common practise by some manufacturers to rigidly attach the stators to the foundation soleplates. This practice would naturally increase the stator radial stiffness. When radial keys are installed, this added rigidity is removed and the remaining stiffness may or may not be sufficient to ensure stability. Thus the need to consider the magnetic stability of the stator in a radial key retrofit.

3.2 Stator and Core Vibration

Loosening the stator from the soleplates reduces its effective stiffness. This stiffness reduction will in turn reduce the natural frequency of the stator assembly. It is important that the natural frequency not coincide with any excitation frequencies or damage to the stator components may occur. The two main excitation mechanisms are tooth frequency and pole frequency excitation:

a) Tooth Frequency:

Fundamental to the understanding of this excitation is the relationship between the slot and pole geometry. Consider a 4 1/5 slots per pole geometry as shown in Fig 7. Since the tooth area projected by each pole varies, the stator experiences a varying magnetic pull from pole to pole. Another property of this magnetic force distribution is that it changes position very quickly with pole position. Typically, movement of one slot pitch will result in a large circumferential movement of the magnetic force wave. This moving force excites the stator core and should be evaluated. The exciting frequency is:

$$\omega_t = Nearest\ Integer\ of\ \left(\frac{Slots}{Poles}\right) 120 \quad (14)$$

(60 Hz Systems)

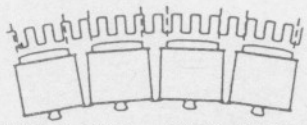

FIGURE 7 POLE - TOOTH RELATIONSHIP

The tooth frequency excitation for a 396 slot, 76 pole machine would be 600 Hz.
The reader is referred to Graham et al (Graham, Beckwith and Milliken, 1931) for a detailed explanation of tooth frequency excitation.

b) Pole Frequency:

Another form of core vibration excitation results from the following combined mechanism:

- The current in the field windings creates a magnetomotive force (mmf). This mmf produces a flux in the generator's magnetic circuit. This magnetic circuit is primarily comprised of the rim, field poles, airgap and stator core. The alternating poles (N & S) on the rim create alternating flux directions as a result of the field winding direction.
- The rotating flux generates a voltage in the stator coils
- If the generator is connected to a load, current will flow in the stator winding as a result of the generated voltage.
- The mmf caused by the current flowing in the stator winding opposes the mmf generated by the field coils. If the field current was not increased (regulated) from the no-load value, the result would be a global reduction in flux and therefore reduced magnetic attraction between the stator core and the field poles
- The reduction in magnetic attraction due to the armature mmf is not uniform from one field pole location to the next field pole location as a result of the manner in which the stator coils are interconnected around the circumference of the stator core (i.e. the winding distribution). This varying reduction in magnetic attraction results in a magnetic force wave being applied to the stator. The frequency of this excitation is close to 120 HZ.

A characteristic of a normal fractional slot machine is that the wavelength of the mmf wave may be quite long. The number of induced waves is given by:

$$i = \frac{Number\ of\ Poles}{L.C.D.\ of\ SPP} \qquad (15)$$

If the natural frequency for i waves in the stator is found to be near 120 Hz, a resonant condition will exist. This situation must be avoided.

c) Stator Natural Frequencies

The stator frame and core can be modelled as rings. Timoshenko (Timoshenko, Young and Weaver, 1974) gives:

$$f_i = \frac{1}{2\pi}\sqrt{\frac{E\,I\,i^2(1-i^2)^2}{\rho A R^4(1+i^2)}} \qquad (16)$$

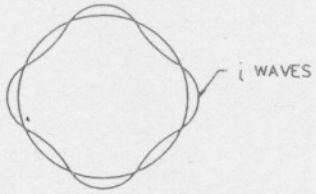

FIGURE 8 VIBRATION MODES

The modes of vibration are as shown in Fig 8.

Equation (16) can be used to estimate the natural frequencies of the core and frame. However, the appropriate values of E,I and A require engineering judgement. For instance, in the analysis of tooth frequency vibration, it may be reasonable to analyze only the core since it is excited at a relatively high frequency under this mechanism and coupling between the core and stator frame may not be significant due to the low amplitude of this vibration.

On the other hand, the pole frequency excitation is at a relatively low frequency and long wavelength and thus coupling of the stator to the core may be assumed.

The analysis of coupled core-stator natural frequencies is complicated by the fact that the stator core is typically constructed of many laminations which are piled in a circle and clamped together. The analysis of a laminated cylinder has been given by White (White, 1961).

3.3 Short Circuit Torque

Very large instantaneous torques can be applied to a stator if a short circuit occurs across the generator terminals. The mechanism causing this torque condition occurs as follows:

- Under normal operating conditions, the pole flux and speed induce rated voltage and current in the armature.
- At the instant the short circuit occurs, there is still rated flux. However, the stator winding circuit impedance is drastically reduced due to the short.
- The low impedance results in a high armature current and thus a high instantaneous torque.
- This initial flux - armature current condition is transient and decays in a time constant relationship to a new equilibrium flux - armature condition at sustained short circuit current and torque. The sustained short circuit torque will be significantly lower than the normal torque since the machine will only be generating the short circuit losses which are typically less than 5 percent of rated output.

The high instantaneous short circuit torque is given by:

$$T_{s.c.} = \frac{2\ T_n}{Xd''} \qquad (17)$$

This torque can be 8 to 10 times T_n

The design of a radial key system must be such that it will withstand the forces generated by this torque.

3.4 Brackets and Auxiliaries

Often the attachment of the stator to the foundation soleplates is not the sole restraining mechanism. The upper bracket, air ducting and main lead assembly can provide substantial restraint. A stiff upper

bracket and stator may require a second sliding joint such as a radial dowel while the air ducting can be addressed with expansion joints. Flexible shunts have been installed to eliminate lead restraint.

3.5 Friction Forces

Installation of radial keys removes the soleplate attachment. The main radial restraining mechanism becomes stator - soleplate friction. The restraining force developed is:

$$F_{fr} = \mu_{sp} F_{app} + \mu_{wk} F_c \qquad (18)$$

This restraining force can be significant enough to lead to distortion of the airgap and therefore should be minimized by reducing the coefficient of friction.

4.0 A Typical Design

Fig 9 details a typical VWW generator radial key retrofit installation:

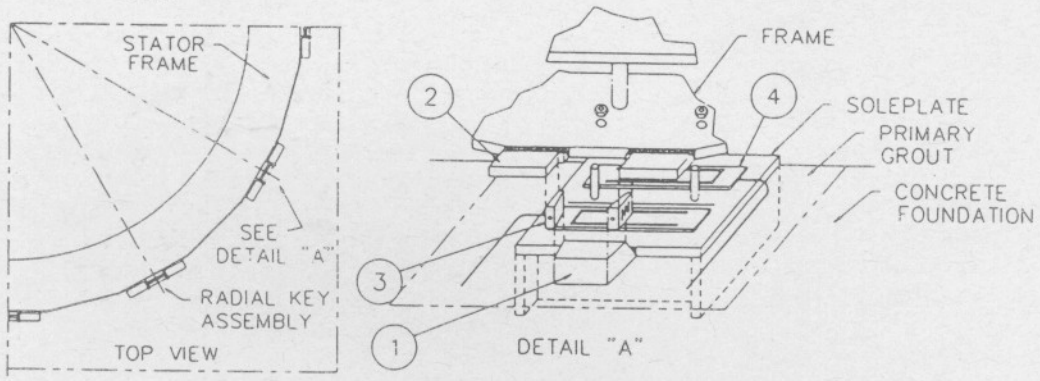

FIGURE 9 TYPICAL VWW GENERATOR RADIAL KEY RETROFIT

The functions of the various components are:

1 - Soleplate Block - Transmits torsional forces to the foundation
2 - Frame Block - Transmits torsional forces from the stator to the wedge keys
3 - Wedge Keys - Provide a low friction close fit between the frame block and soleplate block.
- Provide circumferential adjustment. These keys can be easily removed and refitted to permit re-alignment of the stator frame as required
4 - Slipper Plates - Provide a low coefficient of friction interface between the stator frame and the soleplate

5.0 Spring Assembly to Increase Stator Stiffness

The importance of generator stator radial stiffness has been discussed. During the preliminary analysis of the generator before installing radial keys, one may find the new stator radial stiffness

to result in one of the following situations:

1) The stator is marginal with respect to magnetic stability
2) The stator-core assembly natural frequencies are near the core excitation frequencies.

In these situations, a method of changing the effective stiffness of the stator is required to increase the stator magnetic stability and / or tune the stator assembly away from a resonance condition.

Increased frame stiffness could be obtained by increasing the frame ring depth. However this method would be quite costly and could lead to core wave problems. A method of addressing stator stiffness that is showing promise is to attach radial spring assemblies to the stator. Fig 10 illustrates such an assembly.

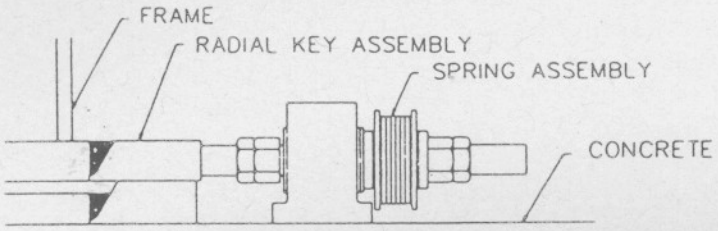

FIGURE 10 STATOR SPRING ASSEMBLY

This assembly has the following benefits:

a) The spring is unidirectional. It pulls but does not push. Thus stiffness is added without inducing core wave.
b) The spring will help ensure uniform expansion of the frame.

6.0 Conclusions:

The radial key retrofit is a relatively simple and effective method for dealing with core wave and concrete creep problems. However, the design and implementation of these systems requires careful attention to the vibration, stability, stiffness and torque characteristics of the generator.

Acknowledgements:

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Nomenclature:

A - effective cross - sectional area
A_c - effective stator core cross-sectional area
A_s - effective stator frame cross-sectional area
B - Flux density
C_p - Pole form factor
C_{stab} - Magnetic Stability Factor
C_u - Units Constant
E - modulus of Elasticity for steel
F_t - Torque Force
Fapp- Applied Force (Stator Wt, Generator Thrust - Conv. Machine, etc)
Fmag- increase in magnetic attraction.
F_{fr} - Friction Force
g - airgap radial length
i - number of waves
I - effective cross-section moment of inertia
I_c - effective core cross-section moment of inertia
K_e - combined rotor - stator stiffness constant
Kmag- magnetic spring constant
Kcbs - Boundary Condition Constant
K_r - rotor radial spring constant
K_s - stator radial spring constant
L.C.D. - Lowest Common Denominator
l - core stack length
p - interface pressure
r - core - stator interface radius
r_s - mean stator frame radius
r_c - mean stator core radius
Rag - mean airgap radius
R - effective radius
SPP - Slot per pole per phase
T_n - Normal Torque
$T_{s.c.}$ - Short Circuit Torque
Xd''- direct-axis sub transient reactance
z - number of core waves
α - coefficient of thermal expansion for steel
δ - decrease in airgap
Δr - increase in rotor radius to increase in magnetic force
Δs - decrease in stator radius due to increase in magnetic force
Δt - total reduction in airgap due to magnetic force
Δtc - stator core temperature rise
Δts - stator frame temperature rise
σ_c - core hoop stress
ρ - mass density
σ_s - stator frame hoop stress
μ_{sp} - soleplate friction coefficient
σ_k - core buckling stress
μ_{wk} - wedge key friction coefficient